Cost-effective Ground Improvement for Liquefaction Remediation near Existing Lifelines

by

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ABSTRACT

Little information has been gathered on ground improvement near existing lifelines. Five low vibration ground improvement techniques suitable for remedial work near existing structures are discussed. The five techniques are compaction grouting, permeation grouting, jet grouting, *in situ* soil mixing, and drain pile. Cost estimates are given for each technique, except the drain pile technique which is not yet available in the United States. Two reported case histories of ground improvement near buried pipes and conduits are reviewed. A combination of techniques may provide a cost-effective solution for preventing damage to existing lifelines resulting from liquefaction-induced horizontal ground displacement, subsidence, and uplift.

KEYWORDS: building technology; earthquake; ground improvement; lifelines; permanent ground deformation; soil liquefaction.

1. INTRODUCTION

One of the major factors of lifeline damage in earthquakes is horizontal ground displacement caused by liquefaction of granular soils, as illustrated in the case studies for many past earthquakes in the United States and Japan (O'Rourke and Hamada, 1992; Hamada and O'Rourke, 1992). Other important factors of liquefaction-induced damage include local subsidence associated with the ejection of soil and water, and flotation of light weight buried structures. For example, horizontal ground displacement damaged many pipelines, roads, bridges, and buildings during the 1906 San Francisco, California, earthquake. Broken water lines made fire fighting after the earthquake impossible, and much of San Francisco burned. During the 1989 Loma Prieta earthquake, liquefaction, horizontal ground movement, major pipeline damage, and fires occurred at virtually the same locations in San Francisco. Of the 160 breaks in the Municipal Water Supply System of San Francisco in 1989, 123 were in the Marina, where significant liquefaction and ground deformation had occurred (O'Rourke and Pease, 1992).

Many lifeline structures lie in regions of high liquefaction and ground displacement potential. While it may be feasible to relocate some support facilities on sites which are not susceptible, similar precautions are not always possible for the long linear element of lifeline systems such as pipelines, electrical transmission lines, and communication lines. For some pipeline systems, such as gas and water lines, it may be economical to install modern welded steel pipes that may not break or leak, even after moderate deformation (O'Rourke and Palmer, 1994). For other pipeline systems, such as waste water lines, the segmented pipe used can accommodate very little deformation. Ground improvement may be the most economical solution for these type of systems, or for areas where large ground deformations are anticipated.

This paper reviews five low vibration ground improvement techniques, and discusses their application to existing lifelines, in particular, pipelines supported by ground having high potential for liquefaction and horizontal ground displacement.

2. LIQUEFACTION REMEDIATION BY GROUND IMPROVEMENT

The risk of liquefaction and ground displacement can be reduced by the following types of ground improvement: densification, solidification, drainage, dewatering, and reinforcement (National Research Council, 1985; Kramer and Holtz, 1991; JSSFME, 1994). Soil densification is generally considered highly reliable, and the most standard remedial measure against liquefaction. It reduces the void space, thereby decreasing the potential for volumetric change that would lead to liquefaction. Resistance to shear deformation also increases

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with increased density. Several sites improved by densification techniques performed well during the 1989 Loma Prieta and the 1994 Northridge, California, earthquakes (Mitchell and Wentz, 1991; Graf, 1992a; Hayden and Baez, 1994).

Solidification is also considered a highly reliable remedial measure against liquefaction. It prevents soil particle movement and provides cohesive strength. During the 1989 Loma Prieta earthquake, the few sites improved by solidification techniques performed well (Mitchell and Wentz, 1991; Graf, 1992a).

While the drainage method has been used for a number of liquefaction remediation projects in Japan, it has found limited use in the United States. Shake table tests (Sasaki and Taniguchi, 1982) indicate that gravel drains can accelerate the dissipation of excess pore water pressures, thereby limiting the loss of shear strength and reducing the uplift pressures acting on buried structures. Following the 1993 Kushiro-Oki, Japan, earthquake, Iai et al. (1994) observed that quay walls having back fill treated by the gravel drain pile and sand compaction pile techniques suffered no damage, while quay walls having untreated backfill were severely damaged due to liquefaction. The drainage method does not prevent seismic-induced subsidence.

Lowering the ground water level by dewatering reduces the degree of saturation, thereby preventing the development of excess pore water pressure which would lead to liquefaction. The dewatering method does not prevent seismic-induced settlement. Dewatering is a difficult task and very expensive, since both upstream and downstream seepage cutoffs are usually required, and pumps must be maintained constantly.

Soil reinforcement provides resistance to ground deformations. Shake table tests reported by Yasuda et al. (1992) indicate that continuous underground walls can control horizontal ground movement. Their effectiveness depends on such factors as quantity, orientation, shear resistances, and excitation direction.

The most commonly used ground improvement techniques are vibro-compaction, vibro-replacement, dynamic compaction, and sand compaction pile. These four techniques improve by densification, and are typically less expensive than other techniques. However, they can produce objectionable levels of work vibration.

3. GROUND IMPROVEMENT TECHNIQUES FOR EXISTING LIFELINES

Techniques selected to improve the ground surrounding or adjacent to existing lifelines should be those that would not cause excessive level of disturbance to the lifelines. Five low vibration techniques which improve ground conditions in one or more of the above ways are discussed in the following paragraphs. A number of advantages and constraints for each technique are listed in Table 1.

3.1 Compaction Grouting

Compaction grouting is the injection of a thick, low mobility grout that remains in a homogenous mass without entering soil pores (Graf, 1992b; Warner et al., 1992; Rubright and Welsh, 1993). As the grout mass expands the surrounding soil is displaced and densified. Recommended grout mixes consist of silty sand, cement, fly ash, and water. Bentonite and other clay materials increase mobility, and their use should be restricted. Cement may not be needed for just soil displacement. For deep injection (greater than about 3 m), final spacings of 2 to 4 m are frequently used. For shallow injection, final spacings usually range from 1 to 2 m. Compaction grouting has been successfully used to correct structural settlement, prevent settlement during soft ground tunneling in urban areas, protect structures against local zones of sinkhole settlement and densify liquefiable soil. The technique is not effective in thick, saturated clayey soils, and may be marginally effective in silt deposits.

3.2 Permeation Grouting

Permeation grouting is the injection under pressure of low viscosity particulate or chemical fluids into soil pore space with little change to the physical structure of the soil (Baker, 1982; Littlejohn, 1993). Particulate grout mixtures may consist of Portland cement, micro-fine cement, clay, fly ash, and water. Chemical grout types include sodium silicates, acrylamides, lignosulfonates, and resins (Karol, 1982). Sodium silicate grouts are the most widely used chemical grout. The acrylamides in solution or powder form, and the catalyst used in all lignosulfonates are toxic. Typical final spacings of grout holes range from 0.5 to 2 m. Permeation grouting has been successfully used to control ground water flow, stabilize excavations in soft ground, underpin existing foundations, and prevent seismic-induced settlement and liquefaction. As a rule-of-thumb, particulate grouts will not permeate most sands, and chemical grouts will not permeate sands containing more than about 25 percent silt and clay. Grout must resist seepage forces, chemical and biological attack, and cracking. Special handling and mixing procedures may be required to insure the health and safety of workers, and to protect the environment.

3.3 Jet Grouting

In jet grouting, high pressure (typically 40 to 60 MPa) fluid jets are used to erode and mix/replace soil with grout (Bell, 1993; Covil and Skinner, 1994; Stroud, 1994). The installation procedure begins with the drilling of a small hole, usually 90 to 150 mm in diameter, to the final depth. Grout, usually a water-cement slurry, is jetted into the soil through small nozzles, as the drill rod is rotated and withdrawn. Bentonite is typically added where low permeability is critical. A continuous flow of slurry from the jet points to the ground surface is required to prevent ground pressures from building up to the jet pressure, leading to ground deformation. Large quantities of waste slurry accumulates at the ground surface. Columns and panels of soil-cement as wide as 3 m have been formed. The technique has been successfully used to underpin existing foundations, support excavations, control ground water flow, and strengthen liquefiable soils. Careful control of operations is required for consistent results. Site pilot studies are highly recommended for this technique, as well as the other four techniques.

3.4 *In Situ* Soil Mixing

In situ soil mixing is the mechanical mixing of soil and stabilizer using rotating auger and mixing-bar arrangements (Jasperse and Ryan 1992; Stroud, 1994; JSSFME, 1994). As augers penetrate the ground, the stabilizer is pumped through the auger shaft and out the tip. Flat mixing bars attached to the auger shaft mix injected stabilizer and soil. Upon reaching the designed depth, a second mixing occurs as augers are withdrawn. The result is high strength, or low permeability, columns and panels. Large augers (up to 4 m in diameter) require more torque, and are generally limited to depths less than about 8 m. For deeper mixing, a single-row of two to four shafts about 1 m in diameter is typically used. The columns and panels are commonly layout in a lattice pattern. The technique has been successfully used to control ground water flow, support excavations, stabilize embankments and slopes, increase bearing capacity for new foundations, and prevent lateral ground displacement caused by liquefaction. Obstructions such as boulders and logs, and hard strata can be a problem.

3.5 Drain Pile

Ono et al. (1991) described a low vibration system for constructing gravel drain piles using a large casing auger. The casing is screwed down into the ground, while simultaneously pouring water into the casing to prevent hydrostatic imbalance and sediment flow into the casing. Gravel is discharged into the casing upon reaching the final depth. As the casing is unscrewed, gravel is pushed out the end of the casing and compacted by a rod. One study showed standard penetration resistances measured at the midpoint between piles after installation were about 5 blow counts higher than before installation. When drains are installed without the compaction rod, little densification occurs. Design charts for determining drain spacings which take well resistance into account have been proposed by Onque (1988). There is no easy way to install filters around gravel drain piles, and drains may clog when liquefaction occurs (Onque et al., 1987). Systems for installing synthetic drains made of plastic and filter cloth have also been developed. For several liquefaction remediation projects in Japan, a densification technique, such as vibro-compaction or sand compaction pile, was used to densify loose soil to within about 20 m of an existing structure, and gravel or plastic drain piles were installed to within a few meters of the structure (Iai et al., 1994; JSSFME, 1994). There are very few cases in which drains were applied to ground having fines content of over 30 percent and coefficient of permeability of less than 0.001 cm/sec. Careful consideration of seepage conditions is required.

3.6 Cost

Cost estimates for four techniques are given in Table 2. Costs are not provided for the drain pile technique, since it is not available in the United States. These estimates are believed to be reasonable starting values for feasibility studies. The injection labor and materials costs are in terms of dollars per cubic meter of improved soil. For compaction grouting and permeation grouting, the total improved volume is assumed a percentage of the volume of grout injected, as noted below the table. For jet grouting and soil mixing, the cost of labor and materials is for the mixed volume. Before a meaningful cost comparison can be made, the required volume of treatment to prevent horizontal ground displacement must be determined from seismic stability analyses. Items such as quality control and verification testing are not included in the values provided in Table 2. The cost of improvement near lifelines will likely be higher given the special considerations listed below.

4. EXISTING LIFELINES

Ground improvement near existing lifelines requires special considerations (Glaser and Chung, 1995) because of the following:

- Work vibrations may damage lifeline, which could have very serious consequences;
- Soil needing improvement is obstructed by the lifeline;
- Scope of work is of large areal extent, yet may be limited to a narrow right-of-way;
- Subsurface conditions will vary greatly along alignment;
- Extent of treatment required to protect lifeline is not known;
- Exact location and condition of buried utilities may not be known; and
- Improvement may adversely affect regional hydrology.

4.1 Case Histories

Reported case histories of ground improvement near existing lifelines are not common. The two cases involving buried utilities that the authors are aware of are reviewed below.

Gazaway and Jasperse (1992) discussed the application of jet grouting to construct a section of an impervious cutoff wall where several underground pipes and fragile conduits crossed at a chemical plant in northern Michigan. A typical section of this crossing is showing in Figure 1. The depth of the cutoff wall is as much as 7.3 m. To ensure closure beneath the larger pipes, the drill rod was rotated and withdrawn at slower rates. Near the smaller and more fragile conduits, column spacings were tightened, and rotation and withdrawal rates increased. Jet pressures as low as 35 MPa were sometimes used for short periods in the immediate vicinity of particularly sensitive conduits. Approximately 530 square meters of cutoff wall was installed by jet grouting in three and a half weeks. No detectable damage occurred to any of the underground utilities from the jetting action.

Scherer and Weiner (1993) described a remediation project involving a concrete effluent channel and three buried concrete pipelines connected to the channel that had settled as much as 190 mm. Joints in the pipelines had opened as a result of the settlement. The diameters of the three pipes were 1.22, 1.52, and 2.13 m. To avoid costly excavation, dewatering, and problems posed by other utilities within the area, pipes were supported and raised with compaction grout pile elements at each joint location or at intervals not exceeding 3 m. First, vertical compaction piles were constructed on each side of the concrete pipe extending from a firm layer at depth to the bottom of the pipe, as shown in Figure 2. Grout was then injected beneath the center of the pipe to lift the pipe. Finally, the interface between the vertical grout columns and pipe was filled with additional grout to establish positive support. Fifty-two vertical and angle grout columns were installed.

4.2 Liquefaction Remediation

Conceptual diagrams showing various types of ground improvement near an underground utility are shown in Figure 3. These diagrams suggest that buried utilities could be protected from subsidence and uplift using permeation grouting or jet grouting. Depending on the constrains summarized in Table 1, horizontal ground movement could be prevented by any one of the five techniques. The extent of treatment is determined from seismic stability analyses. The safe application distance depends on the nature and condition of the lifeline, as well as the level of disturbance which occurs during ground improvement.

5. CONCLUSIONS

Compaction grouting, permeation grouting, and jet grouting are well suited for remedial work beneath existing structures. The *in situ* soil mixing and drain pile techniques are suitable for work near existing structures. Of these five techniques, only jet grouting and *in situ* soil mixing can treat all liquefiable soil types. Compaction grouting may be marginally effective in thick silt deposits. Chemical grouts cannot permeate soils with more than about 25 percent fines, silt and clay. It seems that drains would be ineffective in ground with low permeability. All five techniques are very expensive. However, each can provide a highly cost-effective solution for certain situations.

Upon reviewing the available cases of ground improvement near buried utilities, one quickly becomes aware that very little has been gathered on the subject. With great care, and depending on the nature and condition of the lifeline, permeation grouting and jet grouting could improve soil conditions immediately adjacent to lifelines. Compaction grouting could be applied beneath existing lifelines, but may not sufficiently compact soils immediately beneath them. The *in situ* soil mixing and drain pile techniques could be effectively employed a short distance away from lifelines. A combination of techniques may provide the most cost-effective solution for some systems.

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Table 1. Advantages and Constraints for Five Ground Improvement Techniques.

Advantage or Constraint	Compaction Grouting	Permeation Grouting	Jet Grouting	*In Situ* Soil Mixing	Drain Pile
Produces low levels of work vibration and noise	yes	yes	yes	yes	yes
Soil types not treatable	saturated clayey soils	soils with fines content of over about 25%	irregular geometries in cobbly soils and open gravel	boulders, logs, and hard strata can be a problem	soils with significant fines content and very low permeability
Treatment beneath existing structures possible	yes	yes	yes	earth structures	earth structures
Small diameter drilling	yes	yes	yes	no	no
Low headroom work possible	yes	yes	yes	no	plastic drain pile
Selective treatment possible	yes	yes	yes	no	no
Intimate contact with structure possible	limited	yes	yes	no	no
Treatment at very low confinement possible	marginal	yes	yes	yes	yes
Without care, likely disturbance	significant ground movement; damaged pipes	significant ground movement; damaged pipes	significant ground movement; damaged pipes	significant ground movement; damaged pipes	damaged pipes
Quantity of waste produced	little	little	large	some	some
Prevents seismic-induced subsidence	yes	yes	depends on design	depends on design	no
Well-defined specifications required	yes	yes	yes	yes	yes
Engineered/observational approach required	yes	yes	yes	yes	yes
Quality control during installation required	yes	yes	yes	yes	yes
Other evaluations required	site pilot study	durability; creep; health and safety; site pilot study	durability; site pilot study	durability; site pilot study	seepage; clogging; site pilot study
Can be highly cost-effective	yes	yes	yes	yes	yes
Cost	expensive	expensive	expensive	expensive	expensive

Table 2. Cost Estimates for Low Vibration Ground Improvement Techniques in the United States (based on data from Welsh, 1992; Welsh, 1995).

Method	Mobilization/ Demobilization ($ per drill rig)	Grout Pipe Installation ($ per m of pipe)	Injection Labor and Materials ($ per m^3 of improved soil)
Compaction Grouting	8,000 to 15,000	> 50[a]	> 20[b]
Permeation Grouting Micro-fine cement Silicates	 15,000 to 25,000 > 25,000	 > 50[c] > 50[c]	 > 130[d] > 200[e]
Jet Grouting	> 35,000	-----	> 320[f]
In Situ Soil Mixing	100,000[g]	-----	> 100[h] , > 200[i]
Drain Pile	not available	-----	not available

[a]Grout pipe 76 mm in diameter; cost would double for low headroom work.
[b]Assuming volume of grout injected is 10 percent of the total volume treated.
[c]Sleeve port pipes; cost would double for low headroom work.
[d]Assuming clean gravel with sand, 20 percent grout take, and more than 200,000 liters of grout.
[e]Assuming clean sand, 30 percent grout take, and more than 200,000 liters of grout.
[f]Does not include handling and removal of the waste slurry.
[g]Approximate cost for large multi-auger rig and grout plant.
[h]Shallow mixing (say depths less than about 8 m).
[i]Deep mixing (say depths between 8 m and 30 m).

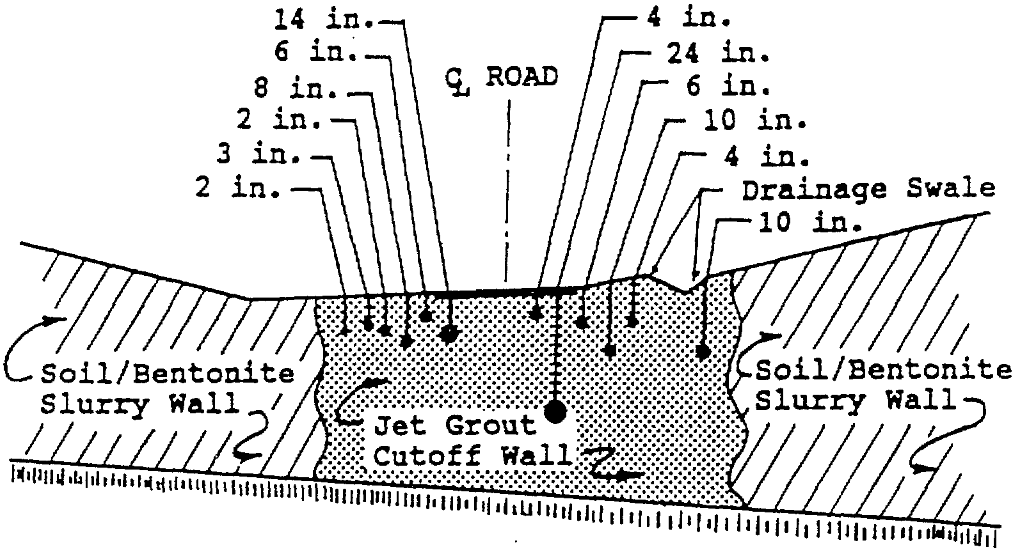

Figure 1. Construction of Cutoff Wall at Utility Crossing by Jet Grouting (Gazaway and Jasperse, 1992). (1 in. ≈ 25 mm.)

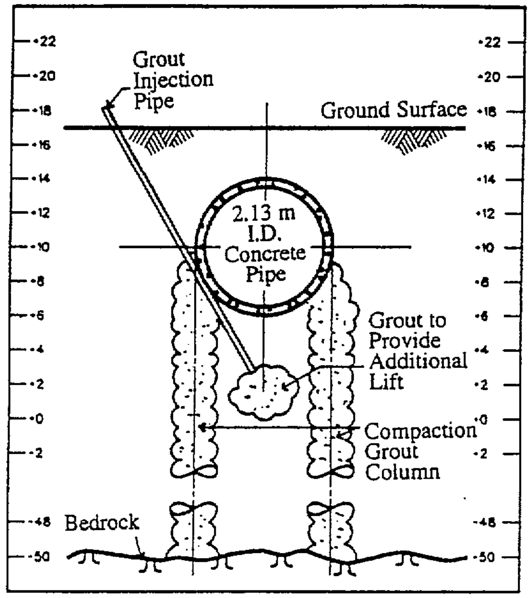

Figure 2. Underpinning and Leveling Settled Pipe by Compaction Grouting (Scherer and Weiner, 1993). (Elevations are in ft; 1 ft ≈ 0.3 m.)

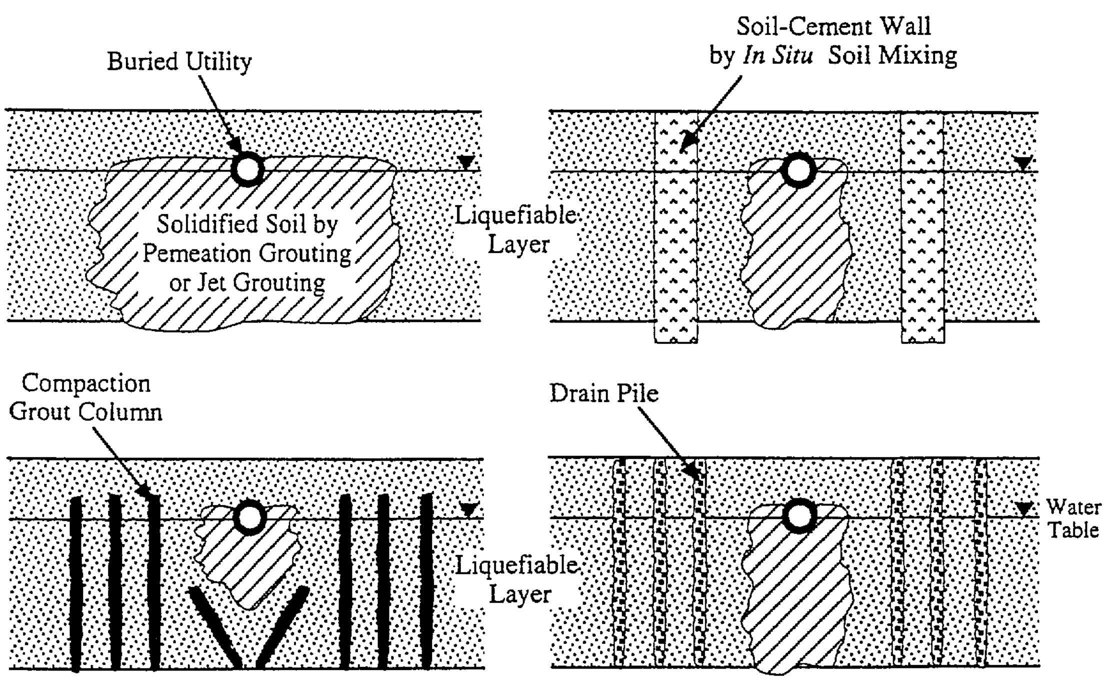

Figure 3. Liquefaction Remediation Near Buried Utility by Combination of Low Vibration Ground Improvement Techniques.